Gluon polarisation and other polarised lepton scattering physics

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Abstract. An overview about recent results from deep inelastic scattering of polarised leptons off polarised protons and neutrons is given. Described are inclusive measurements of the longitudinal spin structure functions, measurements of the photon gluon fusion process to extract the gluon polarisation and measurements with transversely polarised targets to determine the transverse quark distributions. A first measurement of the gluon polarisation via open charm production in the photon gluon fusion process was obtained recently by the COMPASS collaboration. An alternative approach used by several experiments makes use of high p_T hadron pairs to tag the photon gluon fusion process. All results indicate that the gluon polarisation is either small or has a node for x around 0.1. In addition, recent results from proton-proton collisions using longitudinal and transverse beam polarisations are discussed.

Keywords: deep inelastic scattering, structure functions, gluon polarisation, transversity
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INTRODUCTION

In the recent years much effort was put into experiments investigating the spin structure of the nucleon by deep inelastic scattering (DIS) of polarised leptons off polarised nucleons. Initially the measurements were started in the seventies at SLAC and CERN. One of the exciting results was that the contribution of quarks to the nucleon spin is much smaller than anticipated before [1]. These finding initiated a series of DIS experiments at CERN, SLAC, DESY and JLAB (see table 1) where the spin structure of the proton and the neutron was studied in great detail. All these experiments confirmed the original finding that the contribution of quarks to the nucleon spin is small, of the order of 25%. To make up for the total spin additional contributions are necessary. For a nucleon with a helicity $+1/2$ one gets

$$S_\mathrm{p} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_\mathrm{q} + L_\mathrm{G}$$

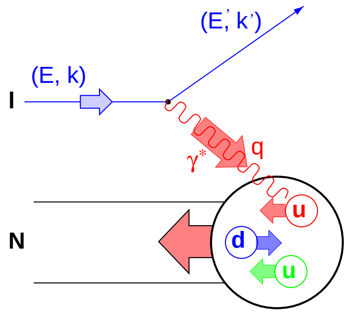
with $\Delta\Sigma = \Delta u + \Delta d + \Delta s$ the contribution of quarks, ΔG the contribution of gluons and $L_{\mathrm{q,G}}$ their orbital angular momenta.

While the contributions of quarks, $\Delta\Sigma$, can be measured in inclusive DIS, the gluon polarisation, ΔG, is accessed e.g. in measurements of the photon gluon fusion process.

To complete the picture of the nucleon, additional knowledge of the transverse quark distributions is required, which can be accessed in semi-inclusive measurements using transversely polarised targets. The orbital angular momentum was not measured up to now, but it may be accessed by measuring generalised parton distributions in exclusive reactions like deeply virtual Compton scattering.

POLARISED DEEP INELASTIC SCATTERING

To investigate the spin structure of the nucleon polarised leptons are scattered off polarised nucleons. The kinematics of the corresponding one-photon exchange process are shown in Figure 1.



$$
\begin{aligned}
Q^2 &= -(k-k')^2 \stackrel{\text{lab}}{=} 4EE'\sin^2\frac{\theta}{2}\\
W^2 &= (P+q)^2 \stackrel{\text{lab}}{=} M^2+2M\nu-Q^2\\
\nu &= \frac{P\cdot q}{2M} \stackrel{\text{lab}}{=} E-E'\\
x &= \frac{Q^2}{2P\cdot q} \stackrel{\text{lab}}{=} \frac{Q^2}{2M\nu}\\
y &= \frac{P\cdot q}{P\cdot k} \stackrel{\text{lab}}{=} \frac{\nu}{E}
\end{aligned}
$$

FIGURE 1. Deep inelastic lepton nucleon scattering in the quark parton model

Here, Q^2 is the negative squared of the four-momentum transfer q by the virtual photon and ν the energy transfer in the laboratory system with $k=(E,\vec{k})$, $k'=(E',\vec{k'})$ and P the four-momenta of the incoming and outgoing lepton and the target nucleon. W is the invariant mass of the hadronic final state. The two Lorentz invariant variables x and y range from 0 to 1. Here, y is the relative energy transfer, and x is interpreted as the momentum fraction carried by the struck quark in the quark parton model [2]. M is the proton mass and θ the scattering angle in the laboratory system.

The produced hadrons are usually described by the fraction of available energy carried by the hadron, $z=E_{\text{hadron}}/\nu$, the transverse momentum relative to the virtual photon direction, p_{T}, and $x_{\text{F}}=2p^*_{\text{L}}/W$ with p^*_{L} the hadron longitudinal momentum in the photon nucleon system.

The cross section is given by the sum of the unpolarised cross section $\mathrm{d}\bar{\sigma}$ depending on the unpolarised structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$ and the polarised contribution $\mathrm{d}\Delta\sigma$ depending on the spin structure functions $g_1(x,Q^2)$ and $g_2(x,Q^2)$. Here, only measurements with longitudinally polarised targets are discussed for the inclusive measurements. Thus, the measurements yield the cross section difference $\mathrm{d}\Delta\sigma_{\parallel}=\mathrm{d}\sigma^{\uparrow\downarrow}-\mathrm{d}\sigma^{\uparrow\uparrow}$. The first arrow depicts the lepton spin, the second one the target spin. In terms of structure functions the cross sections are given by

$$
\begin{aligned}
\frac{\mathrm{d}^3\bar{\sigma}}{\mathrm{d}x\mathrm{d}y\mathrm{d}\phi} &= \frac{4\alpha^2}{Q^2}\left\{\frac{y}{2}F_1+\frac{1}{2xy}\left(1-y-\frac{y^2\gamma^2}{4}\right)F_2\right\}\\
\frac{\mathrm{d}^3\Delta\sigma_{\parallel}}{\mathrm{d}x\mathrm{d}y\mathrm{d}\phi} &= \frac{4\alpha^2}{Q^2}\left\{\left(1-y-\frac{y^2\gamma^2}{4}\right)g_1-\frac{y}{2}\gamma^2 g_2\right\}
\end{aligned}
$$

with $\gamma = 2mx/Q^2$ and α the fine structure constant. The double spin asymmetry $A = \Delta\sigma/2\bar{\sigma}$ are then given by

$$A_{\|}(x,Q^2) = \frac{d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow}}{d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow}}.$$

The longitudinal asymmetry $A_{\|}$ can be interpreted in terms of the absorption of transversely polarised photons with the spin parallel ($\sigma_{3/2}$) or antiparallel ($\sigma_{1/2}$) to the nucleon spin. In the quark parton model the photon nucleon asymmetry $A_1 = (\sigma_{1/2} - \sigma_{3/2})/(\sigma_{1/2} + \sigma_{3/2})$ is given in terms of the distribution of quarks with the spin parallel, $q^+(x)$, or antiparallel, $q^-(x)$, to the nucleon spin

$$A_1 \approx \frac{\Sigma_q\, e_q^2\, (q(x)^+ - q(x)^-)}{\Sigma_q\, e_q^2\, (q(x)^+ + q(x)^-)} = \frac{g_1(x)}{F_1(x)}.$$

Thus, A_1 measures the charge weighted sum of the quark contributions to the nucleon spin, i.e. the spin structure function $g_1(x)$.

The exact relation between the lepton nucleon asymmetry, $A_{\|}$, and the photon nucleon asymmetry, A_1, is given by $A_{\|} = D(A_1 + \eta A_2) = (g_1 - \gamma^2 g_2)/F_1$, where the polarisation transfer, $D = y(2-y)/y^2 + 2(1+R)(1-y)$, from the lepton to the nucleon increases with the relative energy transfer y. $\eta = 2(1-y)\sqrt{Q^2}/(y(2-y)E)$ and γ are kinematic factors and $R = \sigma_L/\sigma_T$ is the cross section ratio for the absorption of longitudinally to transversely polarised photons.

The photon nucleon asymmetry $A_2(x,Q^2) = 2\,\sigma_{LT}/(\sigma_{1/2} + \sigma_{3/2})$ is given by the interference between longitudinal and transverse contributions and has no simple parton model interpretation. But measurements have shown that the second structure function g_2 is small [3]. Together with the fact that the kinematic factor in front is also small for most of the experiments, the second term for $A_{\|}$ can often be neglected so that $A_1 \approx g_1/F_1 \approx A_{\|}/D$.

The experimental asymmetry $A^{\exp} = p_B\, p_T\, f\, D\, A_1$ is typically of the order of 10^{-2} and includes the beam polarisation p_B, the target polarisation p_T, and the dilution factor f which gives the fraction of polarisable nucleons in the target material.

EXPERIMENTS

Up to now all inclusive spin structure measurements were performed at fixed target experiments ranging from 6 GeV electron beams at JLAB to the 200 GeV muon beam at CERN. Table 1 gives an overview about the experiments. Most experiments use solid state targets polarised by dynamic nuclear polarisation at very low temperatures. The target materials were butanol, deuterated butanol, ammonia and ^{6}LiD yielding dilution factors between 0.1 and 0.4. In addition, ^{3}He is used as neutron target. Using a storage cell target with atomic hydrogen and deuterium, dilution factors of about 1 are reached by HERMES [4]. The experiments cover a kinematic range in Q^2 between 1 and 100 GeV^2 at high x, between 0.1 and 1 GeV^2 at x around 0.05 and only a very narrow range in Q^2 for the lowest x down to 10^{-4}.

TABLE 1. List of polarised DIS experiments

SLAC	**E80, E130**	$\vec{e}\,\vec{p}$	≤ 20 GeV
CERN	**EMC**	$\vec{\mu}\,\vec{p}$	100–200 GeV
SLAC	**E142, 143**	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	≤ 28 GeV
CERN	**SMC**	$\vec{\mu}\,\vec{p},\vec{d}$	100, 190 GeV
SLAC	**E154, 155**	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	≤ 50 GeV
DESY	**HERMES**	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	27.5 GeV
CERN	**COMPASS**	$\vec{\mu}\,\vec{d}$	160 GeV
JLAB	**HALL A**	$\vec{e}\,\vec{n}$	6 GeV
JLAB	**CLAS**	$\vec{e}\,\vec{p},\vec{d}$	6 GeV
JLAB	**RSS**	$\vec{e}\,\vec{p},\vec{d}$	6 GeV

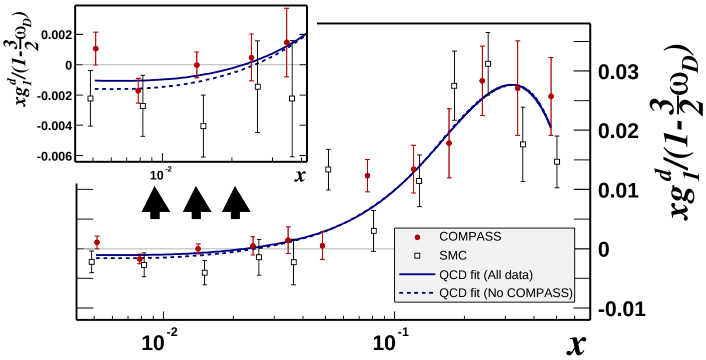


FIGURE 2. COMPASS results for $xg_1^{\mathrm{d}}(x)$ vs. x compared to SMC results. The COMPASS data are given at the measured Q^2, the SMC data are evolved to the same Q^2 and are slightly shifted in x for clarity. The curves are the results of QCD analyses of the world data without and with the COMPASS data.

LONGITUDINAL SPIN STRUCTURE FUNCTIONS

The asymmetry A_1 was measured over the full kinematic range for the proton and the deuteron, while the ^{3}He measurements cover the smaller kinematic region accessible at SLAC and HERMES. Most experiments studied the x and Q^2 dependence of A_1. Up to now no Q^2 dependence of A_1 was observed [5, 6, 7], thus the data are usually averaged over Q^2 and their x dependence is studied.

Recently, several new measurements of spin structure functions were obtained. The COMPASS collaboration measured for $A_1^{\mathrm{d}}(x)$ at low x for $Q^2 > 1$ GeV^2 [7]. From the measured asymmetries the spin structure function $g_1 = A_1 \cdot F_2/[2x(1+R)]$ is extracted using parametrisations of the unpolarised structure functions, F_2 and R. The data were taken in 2002/03 and are compared to the previous SMC results [5]. As can be seen in Figure 2 the new results are much more precise for $x < 0.1$.

A very precise measurement of $A_1^{\mathrm{d}}(x)$ was obtained by the HERMES collaboration [8]. The results are shown in Figure 3 a) in comparison with the other DIS measurements from SMC, E142/3, E154/5, COMPASS and JLAB. The high quality of the new data is clearly visible. The data from SLAC and HERMES cover very similar Q^2 ranges with the HERMES data extending the x range by nearly a decade. The average Q^2 of the

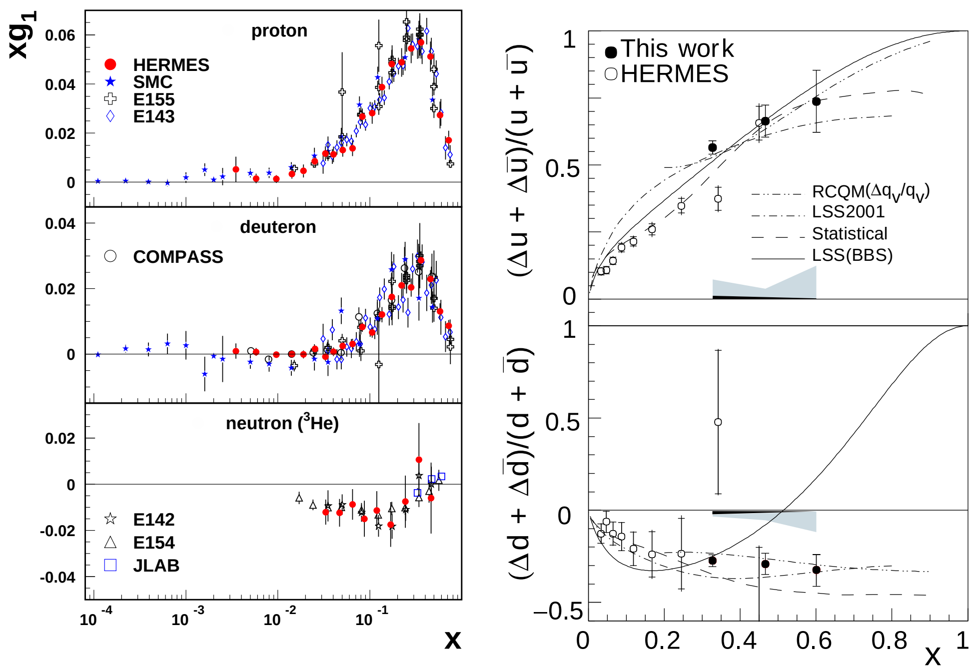


FIGURE 3. a) Compilation of the data for xg_1 of proton, deuteron and neutron including the new HERMES and COMPASS data, b) Results for $(\Delta u+\Delta\bar{u})/(u+\bar{u})$ and $(\Delta d+\Delta\bar{d})/(d+\bar{d})$ from E99-117. The curves are predictions from models and QCD analyses.

CERN muon experiments is generally higher by a factor of the order of 10. Their data also extend to much lower $x \approx 10^{-4}$.

Due to the much lower beam energy DIS experiments at JLAB are performed at considerably higher x. One example is the E99-117 experiment that measured A_1^{n} using polarised ^{3}He targets [9]. The data show very clearly that A_1^{n} is positive for $x > 0.5$. Combining the data with the HERMES data on A_1^{p}, results were obtained for the u- and d-quark polarisations at large x (see Figure 3 b). Perturbative QCD predicts the $\Delta u/u$ and $\Delta d/d$ should approach 1 for $x \longrightarrow 1$ which is not supported by the data. This can be interpreted as a hint for orbital angular momentum contributions in the nucleon.

The interpretation of the results for g_1 in the DIS region is usually done in terms of a next-to-leading-order (NLO) perturbative QCD analysis. The DGLAP evolution equations [10] for the polarised parton densities are used to describe the Q^2 dependence of g_1 e.g. in terms of polarised singlett, $\Delta\Sigma = \sum_{i=1}^{n_f} \Delta q_i$, non-singlett, $\Delta q_{NS} = \sum_{i=1}^{n_f} \left(e_i^2/\langle e^2\rangle - 1\right)\Delta q_i$, and gluon distributions, Δg [11]. Alternatively valence quark, sea quark and gluon distribution can be used [12, 6]. From the analyses the first moment of the singlett contribution can be estimated, e.g. a value of $\Delta\Sigma = 0.213 \pm 0.138$ at $Q^2 = 1\,\mathrm{GeV}^2$ is obtained in [12]. The gluon distribution is much less constraint than the quark distributions due to the limited lever arm in Q^2 of the polarised data compared to the unpolarised ones, especially in the low x range which is most sensitive to the gluon distribution. Typical values for ΔG of the order of 0.5 – 1 were obtained with an error of the order of 100% (see e.g. [6]), thus direct measurements are urgently needed.

GLUON POLARISATION

In DIS the gluon distribution is accessible via the photon gluon fusion process (PGF) (see Figure 4 left). A few years ago several activities were started to determine ΔG either from open charm production or from high p_T hadron pairs [13] by SMC, HERMES and COMPASS. Alternatively the gluon polarisation can also be measured in collider experiments using polarised protons.

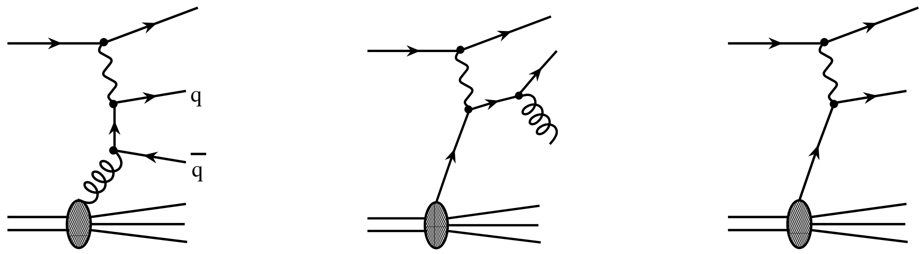


FIGURE 4. Lowest order diagrams for γ^* absorption: a) photon gluon fusion, b) QCD Compton and c) leading process.

The COMPASS collaboration used open charm production and high p_T hadron pairs to study the gluon polarisation. In the measurement of open charm production only the process $\gamma g \to c\bar{c}$ is selected by requiring charmed mesons (D^0, D^*) in the final state. The mass of the charm quark serves as hard scale, thus the full Q^2 range down to quasi-real photon absorption can be used. The mesons are reconstructed by their subsequent decays, e.g. $D^0 \to \pi K$ (BR: 4 %). Unfortunately the branching ratios of the best channels are low. Due to the long solid state polarised target the reconstruction of the D meson decay vertex is not possible. They are reconstructed from the invariant mass distribution only. This method is hampered by a huge combinatorial background below the D^0 peak. Selecting D^* first by adding a slow π suppresses much of the background (see Figure 5 left). The gluon polarisation is calculated from the measured asymmetry by $A_{LL} = p_B\, p_T\, f\, a_{LL}\, S/(S+B) \cdot \Delta G/G$. The analysing power a_{LL} is extracted from a Monte Carlo simulation using the AROMA generator. A value of $\Delta G/G = -1.08 \pm 0.73(\text{stat.})$ at $x_g = 0.15$ is obtained from the 2002/03 COMPASS data.

The alternative approach using high p_T hadron pairs makes use of all PGF events $\gamma g \to q\bar{q}$ with all quark flavours q. To ensure a perturbative interpretation a hard scale is set by the requirement of a high transverse momentum, p_T, for the produced hadrons. To enhance PGF events the hadrons should have opposite charge and azimuth. Previously, results for high p_T asymmetries were obtained by EMC [14] for $Q^2 > 1$ GeV^2 and HERMES [15] using all Q^2. The COMPASS collaboration performed two independent analyses, one for $Q^2 < 1$ GeV^2 and one for $Q^2 > 1$ GeV^2.

To extract $\Delta G/G$ from the measured asymmetries of high p_T hadron pairs several background processes have to be accounted for (see Figure 4) like the leading process and QCD Compton process. In addition, resolved photon processes and vector meson production have to be taken into account for small Q^2. The relative contributions are determined by Monte Carlo simulations leading to an additional contribution to the

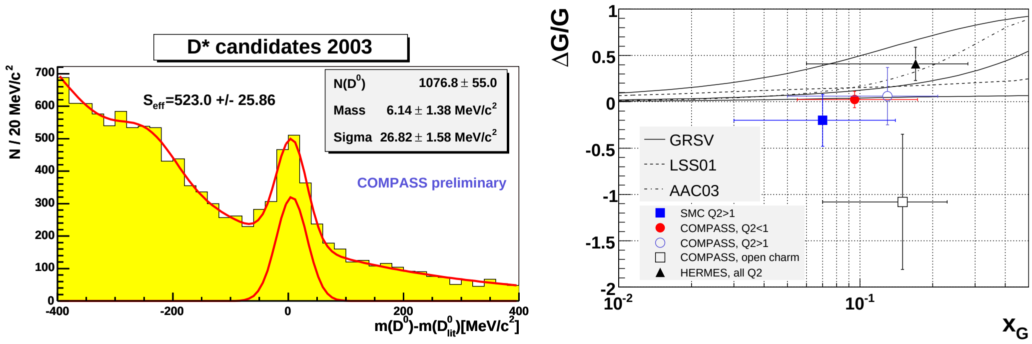


FIGURE 5. Left: Invariant mass distribution in the D^0 mass range using D^* candidates. The effective signal is given by $S_{\mathrm{eff}} = S/(1+S/B)$. Right: Compilation of the results for $\Delta G/G$ from high p_{T} hadron pairs and open charm production. In addition a few parametrisations from recent QCD analyses are shown [12, 23, 24].

systematic error. After all cuts the fraction of PFG events is of the order of 30 % for all experiments.

For $Q^2 > 1\ \mathrm{GeV}^2$ a value of $\Delta G/G = 0.06 \pm 0.031(\mathrm{stat.}) \pm 0.06(\mathrm{syst.})$ is obtained with the help of a LEPTO Monte Carlo from the measured asymmetry $A_{\parallel}/D = -0.015 \pm 0.080(\mathrm{stat.}) \pm 0.013(\mathrm{syst.})$ at $x_{\mathrm{g}} = 0.13$ [16]. There are 10 times more events if one uses the low Q^2 events for the analysis leading a more precise value of $A_{\parallel}/D = 0.002 \pm 0.019(\mathrm{stat.}) \pm 0.003(\mathrm{syst.})$ [17]. But to extract the gluon polarisation background processes with e.g. resolved photons have to be accounted for, thus knowledge of the polarised parton distributions in the photon is required. As these are still unknown, their contribution was estimated using the unpolarised parton distributions in the photon. The resulting gluon polarisation is $\Delta G/G = 0.024 \pm 0.089(\mathrm{stat.}) \pm 0.057(\mathrm{syst.})$. The systematic error includes the experimental systematics, the systematic errors from the Monte Carlo simulation using the PYTHIA generator and the estimate of the photon contribution. The results for $\Delta G/G$ are summarized in Figure 5 right indicating that $\Delta G/G$ is small or that ΔG had a node around $x_{\mathrm{g}} \sim 0.1$.

PHENIX [18] and STAR [19] at RHIC are taking data with longitudinally polarised 200 GeV protons since 2003. Their goal is the extraction of $\Delta G/G$ from prompt photon production $\mathrm{gq} \to \gamma\mathrm{q}$. Due to the limited statistics of these first longitudinal runs the analysis started with other channels. STAR studied $\mathrm{gq} \to \mathrm{gq} \to 2\,\mathrm{jets}$ [20] and PHENIX $\mathrm{gq} \to \mathrm{gq} \to \pi^0 X$ [21]. While the STAR analysis is still ongoing, results were obtained for π^0 asymmetries at central rapidities from PHENIX. The unpolarised π^0 production cross section was determined and shows good agreement with NLO pQCD calculations for the whole range of transverse momenta [22]. The observed asymmetries, A_{LL}, are small and slightly negative, but still compatible with zero [21]. Several hard subprocesses like $\mathrm{gg} \to \mathrm{gg}$ and $\mathrm{gq} \to \mathrm{gq}$ contribute to π^0 production. The processes most important at central rapidities have a positive partonic asymmetry. Therefore the results hint to a small gluon polarisation like e.g. the standard gluon distribution in [23]. These results illustrate the potential of the π^0 measurements to constrain ΔG when the data are improved with further measurements.

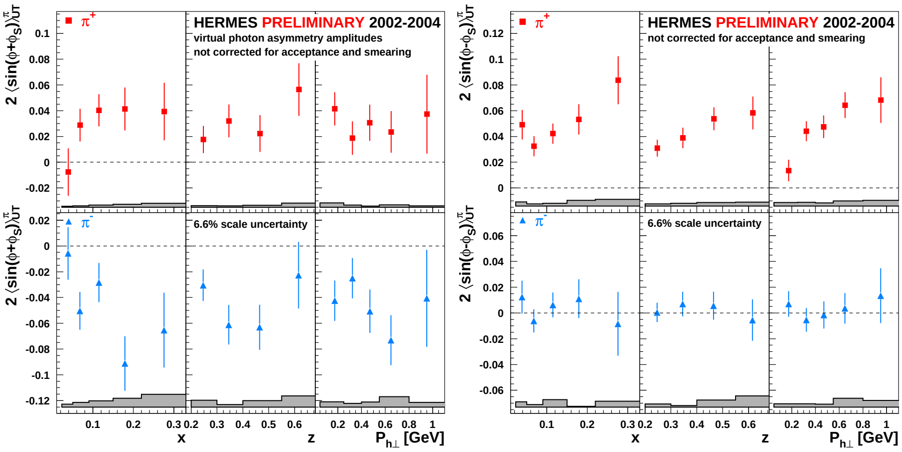


FIGURE 6. Preliminary HERMES results for the Collins (left) and Sivers (right) asymmetries for π^+ and π^- production vs x, z and p_T obtained with a transversely polarised hydrogen target.

TRANSVERSITY

The transverse quark distributions, $\Delta_T q(x)$, are the only leading twist distributions which cannot be accessed by inclusive measurements since they are chirally odd quantities. But in semi-inclusive DIS or proton-proton collisions they can couple to another chirally odd function, so that interesting effects are expected when measuring with transversely polarised targets.

In DIS transversity is investigated by measuring the azimuthal angular target spin asymmetry in the distribution of the produced hadrons. Such measurements have been started at HERMES and COMPASS. In leading twist there are two contributions to such a measurement. One stems from the transverse quark distributions and a chirally odd fragmentation function (Collins FF), the other originates in the Sivers distribution function related to transverse momenta of the struck quarks combined with the normal unpolarised fragmentation function.

On transversely polarised targets the two contributions can be distinguished by calculating moments of the measured azimuthal asymmetries, $\sin(\phi - \phi_S)$ moments for the Sivers functions and $\sin(\phi + \phi_S)$ moments for the Collins functions. Here, ϕ is the angle between the lepton and the hadron plane and ϕ_S the angle between the transverse component of the target spin and the lepton plane.

Since 2002 HERMES is taking data with a transversely polarised hydrogen target. The asymmetry $A_{UT}(\phi, \phi_s)$ was determined for $\pi^{\pm}$ identified with the RICH and for π^0 [25, 26]. The Collins and Sivers asymmetries were fitted simultaneously. The results of the x, z and p_T dependence for $\pi^{\pm}$ are shown in Figure 6. Sizeable Collins asymmetries were observed for π^+ and surprisingly also for π^-. A possible explanation of this effect is an unusual ratio of unfavoured to favoured Collins fragmentation functions of about -1. The Sivers moments were found to be positive for π^+ and π^0, while they are compatible with 0 for π^-. This might be related to non-vanishing orbital angular momenta of the quarks.

COMPASS devotes about 20% of the data taking to measurements with a transversely

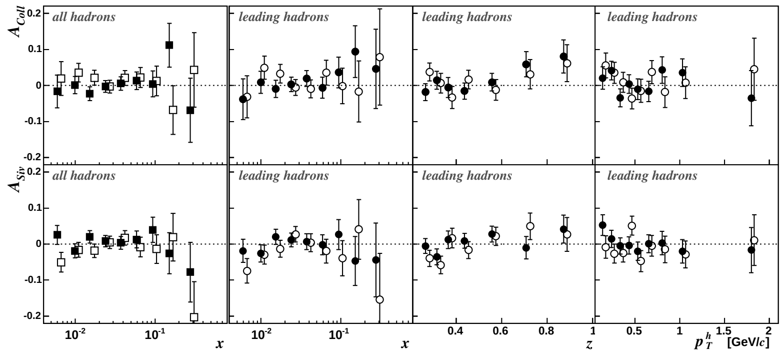


FIGURE 7. COMPASS results for the Collins (upper) and Sivers (lower) asymmetries of positive and negative hadrons vs x, z and p_{T} obtained with a transversely polarised deuteron target.

polarised ^{6}LiD target. Results from the first transverse run in 2002 are shown in Figure 7 [27]. In the analysis events with $Q^2 > 1$ GeV^2 and a leading hadron with $z > 0.25$ were selected. The x, z and p_{T} dependence of the Collins and Sivers moments was studied for positive and negative hadrons. All asymmetries are comparable with 0 within statistical errors hinting to some cancellation for the deuteron target.

To disentangle the unknown transverse quark distributions and the unknown fragmentation functions more experimental inputs would be helpful, e.g. an independent measurement of the Collins fragmentation function. Such a measurement can be done with e^+e^- collisions. Azimuthal asymmetries in pion pair production are sensitive to the Collins fragmentation function. The BELLE collaboration has investigated their off-resonance data for such asymmetries [28]. Significant asymmetries rising with z were obtained using different methods to suppress background contributions and provide cancellation of acceptance effects. The results give a clear hint to a non-zero Collins fragmentation function.

Transverse asymmetries were also studied in pp-collisions at RHIC. STAR, PHENIX and BRAHMS are taking data with transversely polarised protons since 2002. Asymmetries for $\pi^{\pm}$ and π^0 were obtained for different ranges in x_{F}. While the asymmetries seem to be close to zero for negative x_{F} and $x_{\mathrm{F}} \approx 0$, large asymmetries were measured for $x_{\mathrm{F}} > 0$ [30, 29, 31]. But, Sivers and Collins contributions to the measured asymmetries cannot be disentangled as easily as for semi-inclusive DIS. Thus, more data and further theoretical studies are needed in order to discuss the full implication of the results.

SUMMARY

Spin physics is a very active field in fixed target DIS experiments as well as in pp-collider experiments. Until now mainly inclusive DIS measurements were done yielding results for spin structure functions. High precision data are available allowing detailed NLO pQCD analyses. At present, most emphasis lies on semi-inclusive DIS measurements. Data with longitudinally polarised targets are used to determine the gluon polarisation using the photon gluon fusions process. Results have been obtained using high

p_T hadron pairs to tag the photon gluon fusion process. Also, a first measurement using open charm production was done by the COMPASS collaboration. The results indicate that the gluon distribution is either small or has a node around x_g around 0.1. Semi-inclusive measurements with transversely polarised targets have been started to extract the transverse quark distributions. Transversity and the gluon polarisation are also investigated in polarised pp-collider experiments at RHIC.

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